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RESEARCH MEMORANDUM

EFFECT OF RAM-JET PRESSURE PULSATIONS ON SUPERSONIC-DIFFUSER PERFORMANCE

By James F. Connors

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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RESEARCH MEMORANDUM

EFFECT OF RAM-JET PRESSURE PULSATIONS ON SUPERSONIC-DIFFUSER PERFORMANCE

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SUMMARY

An experimental investigation to determine the effects of pressure pulsations on diffuser performance has been conducted on an 8-inch ram jet at a Mach number of 1.87. Several burner designs employing 62-octane gasoline fuel-injection systems and an annular regenerative burner using propylene oxide as a fuel were studied. In addition, a program of mechanically controlled oscillation was conducted wherein the amplitude and the frequency of the pressure pulsations were systematically varied.

It was found that shock oscillations, generated by pressure pulsations from the combustion chamber, precluded the attainment of mean pressure recoveries that were equal to the optimum steady flow value. The annular regenerative burner, however, operated with such a low order of pressure pulsations that the resultant decrement in diffuser pressure recovery was very small (approximately 1 percent of the optimum steady-flow value). In both combustion and mechanical oscillation experiments, the optimum mean combustion-chamber static pressure decreased from the optimum steady-flow value by one-half the total amplitude of the pulsation and occurred when the maximum instantaneous combustion-chamber static pressure equaled the optimum steady-flow value.

A pronounced attenuation of the cold-buzz pressure fluctuations was achieved over a limited range of outlet-inlet area ratios by means of a properly tuned rotating disk located in the combustion chamber. With a disk size equal to 30 percent of the combustion-chamber area, the total amplitude of the pulsation was reduced by 92 percent and the ratio of mean combustion-chamber static- to free-stream total pressure was increased by 7.4 percent. The degree of cold-buzz attenuation varied inversely with the size of the disks investigated.

INTRODUCTION

Experimental performance evaluations of the various supersonic diffusers have often been determined under simulated engine conditions, wherein mechanical outlet-area restrictors have been used to offer a steady flow-resistance to the air stream. This technique thereby presumed the attainment of a smooth combustion process as a requisite for optimum shock location within the diffuser. Preliminary combustion studies (references 1 to 4) have indicated, however, that severe penalties in optimum mean total-pressure recovery may be brought on by combustion roughness (pressure fluctuation) and attendant shock oscillation. Although these pressure fluctuations in the ram jet may be minimized or even eliminated with proper design of the combustor, it is nevertheless important to determine the nature and extent of the resultant penalties incurred during rough burner operation.

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Ram-jet combustors usually have some degree of inherent roughness associated with the particular designs and the various conditions of pressure, temperature, and velocity encountered in flight. Consequently, a study was undertaken at the NACA Lewis laboratory to establish a basis for predicting the decrement in optimum mean pressure recovery for any specified roughness characteristics. An 8-inch ram-jet engine was investigated in conjunction with several combustor designs using liquid fuel injection and also with an annular regenerative burner design. In order to study more intimately the nature of pulsing and its detrimental effect on diffuser operation, a program of controlled mechanical oscillations was then undertaken wherein the amplitude and the frequency of the pressure fluctuations could be varied systematically. A simple rotating disk mounted in the combustion chamber was used to generate the desired oscillation. Amplitudes were determined by the size of the disk, and frequencies were varied from approximately 30 to 120 cycles per second.

APPARATUS AND PROCEDURE

The experimental investigation was conducted in the NACA Lewis 20-inch supersonic tunnel, operating at a Mach number of 1.87 ± 0.04. The test-section stagnation pressure was approximately 28 inches of mercury absolute (pressure altitude, 45,000 ft). By throttling the air with the upstream tunnel valve, the stagnation pressure could be reduced to 18 inches of mercury absolute (pressure altitude, 55,000 ft). For these two altitude conditions the Reynolds number, based on the diffuser-inlet diameter was 1.79×10^6 and 1.15×10^6, respectively. The total temperature of the air stream was maintained at $210^\circ \pm 5^\circ$ F and the dew point at $-10^\circ \pm 10^\circ$ F.

1400 A schematic diagram of the 8-inch ram jet with an adjustable exhaust nozzle is presented in figure 1(a). The engine inlet consisted of a shock diffuser employing a single-shock projecting cone with no internal contraction. With optimum shock location, the diffuser was designed for a combustion-chamber-inlet Mach number of 0.162 and a total-pressure recovery of 0.91 (excluding subsonic-diffuser losses). An adjustable exhaust nozzle actuated by a remotely controlled jack-screw served as a variable restrictor for both hot and cold experiments.

Three different burner designs (fig. 1(b)) were used in conjunction with 62-octane gasoline fuel-injection systems. The burners, which blocked 50 and 60 percent of the combustion-chamber area, were scaled down from combustor designs that had previously performed well in free-jet studies of a 16-inch ram jet. Fuel was injected in an upstream direction by means of commercial spray nozzles located upstream of the flame holder. Among the several injector design variations investigated were a double-ring manifold with nine-spray nozzles assigned to equal segments of cross-sectional area and a single-ring manifold with five spray nozzles located at 60-percent radius (region of highest velocity). Both manifolds were studied with and without flared tips on the nozzles (reference 5). Ignition was produced by an oxacetylene pilot system built into the center of each flame holder.

The annular regenerative burner is shown in figure 1(c). As indicated by the arrows on the upper portion of the figure, the fuel (propylene oxide) entered the 5/8-inch supply tube and was directed to the downstream end of the annular chamber. From this point, the fuel traversed a helical passage until it was ejected through a peripheral orifice to the outside and the inside of the cylinder. When the fuel was injected into the air stream, ignition was effected by the four oxyacetylene pilots located on the support strut. This design of rather arbitrary dimensions had only to allow enough heat to be transferred to the main fuel so that flashing to the vapor phase occurred upon expansion through the peripheral orifice. Too much or too little heat transfer to the fuel resulted in vapor lock or injection in the liquid phase, respectively, either of which caused rough combustion.

A photograph of the rotating-disk oscillator mounted in the combustion-chamber of the 8-inch ram jet is presented in figure 1(d). The investigation extended over a range of disk sizes from 30 to 75 percent of the combustion-chamber area and a range of frequencies from 30 to 120 cycles per second. Pressure fluctuations were produced by the varying flow resistance across the disk as it was rotated between the full-open and full-closed positions. A small air motor mounted external to the tunnel wall served as a drive for the disks, and an electric tachometer was used to measure the rate of rotation. 1400

For pressure measurements, a survey rake of 40 pitot-static tubes arranged in eight symmetrical radial rows was located at the combustion-chamber inlet. The tubes were located at the centroids of 40 equal segments of cross-sectional area. Due to the long lines from the model to the manometer boards, any pressure fluctuations in the engine were damped out and the indicated pressures on the manometer board corresponded to the mean integrated value of the instantaneous pressure wave (reference 4). All pressures were photographically recorded from a differential multitube manometer using tetrabromoethane as the working fluid.

Instantaneous combustion-chamber pressures were measured with a gage consisting of four unbonded strain gages, connected in a wheatstone bridge arrangement, to which the oscillating pressures were transmitted by means of a metallic bellows. The electric signal was fed into a direct-current amplifier and thence to a magnetic-type pen recorder. In this manner, quantitative measurements of fluctuation amplitudes, frequencies, and absolute pressure level were obtained.

At the engine inlet, a two-mirror shadowgraph system was set up to allow for observation of the shock wave patterns. High-speed photographs were taken with a 16-millimeter camera operating at approximately 2500 frames per second.

During the cold steady-flow tests and the oscillator studies (in which the frequency was held constant), the exhaust-nozzle area was varied over the required range to obtain data at and on either side of the optimum mean pressure recovery condition. In the combustion studies, fuel flow was used to vary the back pressure on the diffuser while the exhaust-nozzle area was maintained at a fixed value.

SYMBOLS

The symbols used in this report are defined as follows:

A area, square inches

A_1 diffuser-inlet area with cone removed ($= \pi(5.006)^2/4$) square inches

f frequency, cycles per second

M Mach number

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p static pressure, inches mercury absolute

Δp total amplitude (maximum minus minimum instantaneous static pressure), inches mercury

P total pressure, inches mercury absolute

W_f fuel flow rate, pounds per hour

Subscripts:

0 free-stream condition

1 station at diffuser-inlet

3 station at combustion-chamber inlet (diffuser outlet)

4 station at exhaust nozzle

m optimum mean value with unsteady flow

s optimum steady-flow value

RESULTS AND DISCUSSION

Steady-Flow Diffuser Performance

The results of a typical cold run, in which the back pressure on the diffuser was varied by means of a mechanical outlet-area restrictor, are shown in figure 2, where the combustion-chamber static pressures are presented as a function of combustion-chamber-inlet Mach number. An instantaneous static-pressure measurement was found to be more indicative of the changing test conditions than a single instantaneous pitot measurement because the static-pressure distribution across the duct remained relatively flat and uniform for the various combustion-chamber velocity profiles. The data are therefore presented in terms of the nondimensional static-pressure parameter p_3/P_0. The values of combustion-chamber Mach number were based on average pitot-static manometer pressures. As indicated in figure 2, the experimental optimum mean static-pressure parameter of 0.875 showed close correlation with the theoretically predicted value of 0.89, based solely on shock losses. The displacement of the experimental data in the supercritical region to the right of the theoretical curve may be attributed to a reduction in effective flow area due to boundary-layer build-up at the diffuser outlet. As indicated by the instantaneous pressure data, the total amplitude of the cold-buzz pressure fluctuations was as great as 24 percent of the free-stream total pressure in the subcritical range. The cold-buzz frequency (fig. 3) varied from 19 to 30 cycles per second with decreasing values of outlet-inlet area ratio A_4/A_1. During supercritical steady-flow operation of the diffuser, there were no measurable combustion-chamber pressure fluctuations. 1400

8-Inch Ram-Jet Combustion Experiments

The variation of combustion-chamber static pressures with fuel-flow rate at a constant value of exhaust-nozzle area is shown in figure 4 for a typical combustion experiment with liquid fuel-injection burners. As indicated by the instantaneous pressure-gage data, the amplitude of the pressure fluctuations increased with increasing fuel flow W_f and the optimum mean combustion-chamber static pressure occurred when the maximum instantaneous static pressure equaled the optimum steady-flow value. Based on a calculated mass air flow for a maximum free-stream tube of air entering the engine, the fuel-flow range of 300 to 500 pounds per hour corresponded to an approximate range of mean fuel-air ratios from 0.023 to 0.038 during supercritical operation.

Comparative optimum mean total-pressure recoveries obtained with the liquid fuel-injection burners and the annular regenerative burner are shown in figure 5. All the data for the liquid fuel-injection burners fell on a common curve within the limits of experimental accuracy. As in the 3.6-inch ram-jet experiments (reference 4), a pronounced decrease in optimum mean total-pressure recovery occurred with decreasing values of total-pressure recovery without combustion or, equivalently, with increasing exhaust-nozzle area. Several variables in the combustor design were studied in an effort to obtain a smoother combustion process and, as a result, to attain a higher level of mean pressure recovery. The design changes included three different flame holders, two fuel-injector designs, spray-nozzles with and without flaring, and increasing the distance between the flame holder and the point of injection from 1.5 to 3 combustion-chamber diameters. None of these changes produced any noticeable reduction in the degree of combustion roughness or improvement in the performance of the diffuser with combustion.

The annular regenerative burner with propylene oxide as the fuel produced a lower order of pressure fluctuations than the liquid fuel-injection burners and with its use a marked improvement in diffuser

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performance with combustion was realized. As indicated by the data in figure 5, values of optimum mean total-pressure recovery with combustion that closely approached the optimum steady-flow value were obtained.

Rotating-Disk Oscillator Experiments

In order to simulate varying degrees of combustion roughness, a mechanical oscillator was located in the position that the flame holder occupied during the combustion experiments. The pressure rake, which was mounted approximately 2.0 diameters upstream of the rotating disk, showed no indications of asymmetrical flow or other distortion of the velocity profile. Data from typical oscillator experiments are presented in figure 6, where the combustion-chamber static pressures are plotted as a function of the combustion-chamber-inlet Mach number at a constant oscillator frequency. As in the combustion experiments, the optimum mean combustion-chamber static pressure occurred when the maximum instantaneous static pressure equaled the optimum steady-flow value. In the supercritical range of operation the total amplitude of pulsing Δp_3 remained approximately constant with combustion-chamber Mach number M_3 for any specified frequency. Values of optimum mean combustion-chamber static pressure decreased with increasing amplitudes of pressure fluctuation Δp_3. Similar experimental data were obtained for a range of disk sizes between 30 and 75 percent of the combustion-chamber area and for a range of frequencies between 30 and 120 cycles per second. In each case the optimum mean static-pressure parameter $(p_3/P_0)_m$ appeared to be independent of the frequency of the mechanical oscillations.

Correlation and Extrapolation of Pressure Fluctuation

Data Obtained with and without Combustion

In an actual engine, the variation of the total amplitude of pulsation Δp_3 with combustion-chamber-inlet Mach number is primarily a function of the combustion process. However, in order to establish a basis for predicting the magnitude of the optimum mean pressure recovery as a function of specified roughness characteristics, a relation must be established between the optimum steady-flow static-pressure parameter and the optimum mean static-pressure parameter with the various amplitudes and frequencies of pressure pulsations. Such a relationship is indicated in figure 7, where the decrement in the optimum mean combustion-chamber static-pressure parameter $\left[(p_3)_s - (p_3)_m\right]/P_0$ is presented as a function of the ratio of the total amplitude of pulsation to the free-stream total pressure. The equation for the solid line in figure 7 was based on the assumption 1400 that the integrated mean of the pressure-time diagram would be equal to the average of the maximum and minimum instantaneous pressures. All the test points including data taken with the oscillator at a tunnel pressure altitude of 55,000 feet and data for the 3.6-inch ram jet in reference 4 fell, within the experimental accuracy, on the solid line. Thus, in both combustion and mechanical oscillation experiments, the decrement in optimum mean combustion-chamber static pressure was equal to one-half the total amplitude of the pulsation. Within the range of the variables investigated, this simple relation appeared to hold independent of the origin or frequency of the pressure pulsations.

In order to interpret this result in terms of total rather than static-pressure recovery, the following equation may be used:

$$\left(\frac{p_3}{P_0}\right)_m = f(M_m)\left[\left(\frac{p_3}{P_0}\right)_s \frac{1}{f(M_s)} - \frac{1}{2}\frac{\Delta p_3}{P_0}\right] \tag{1}$$

where

$$f(M) = \frac{P}{p}$$

Within the experimental scatter of the data it was observed that the supercritical portion of the diffuser curve of mean p_3/P_0 as a function of M_3 was approximately the same for both the steady and nonsteady flow cases. This observation was also noted in reference 1. Thus the value of M_m may be approximated by locating $(p_3/P_0)_m$ on the steady-flow diffuser curve $\left[(p_3/P_0)_m = (p_3/P_0)_s - \frac{1}{2}\frac{\Delta p_3}{P_0}\right]$ and then obtaining the corresponding Mach number M_m. For small amplitudes of pulsation or for combustion-chamber Mach numbers much less than unity, $f(M_m) \approx f(M_s)$ and

$$\left(\frac{p_3}{P_0}\right)_m \approx \left(\frac{p_3}{P_0}\right)_s - f(M_s)\,\frac{1}{2}\frac{\Delta p_3}{P_0} \tag{2}$$

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The error involved in using the foregoing approximation instead of equation (1) was less than 1 percent for pressure fluctuation amplitudes ΔP_3 up to approximately $0.25\ P_0$.

For a specified amplitude, then, the decrement in optimum mean pressure recovery varies with the magnitude of the free-stream total-pressure. The detrimental effect of ram-jet pressure pulsations (at specified amplitude) on diffuser performance is magnified as changes in the flight conditions (Mach number and altitude) result in reduced values of free-stream total pressure.

Attenuation of Cold Buzz Pressure Fluctuations

In studying the effect of the oscillator on the subcritical operation of the diffuser, it was found that a rotating disk, when tuned to a critical frequency, caused a marked attenuation of the cold-buzz pressure fluctuations. Instantaneous pressure-time diagrams (fig. 8) show the pressure fluctuations obtained with three different disk sizes, each under the following conditions at a constant exhaust-nozzle area: (1) disk locked in full-closed position, (2) disk locked in full-open position, and (3) disk rotating at a frequency tuned for minimum amplitude Δp_3. With the smallest disk size equal to 30 percent of the combustion-chamber area, the total amplitude of cold-buzz pulsing was reduced by 92 percent and the value of the mean combustion-chamber static-pressure parameter p_3/P_0 was increased by 7.4 percent when the oscillator was tuned to a frequency of 106 cycles per second. The frequency of tuning was critical and restricted to a narrow band. On either side of the critical tuning frequency, the amplitude of the pulsations and the mean combustion-chamber static-pressure parameter p_3/P_0 were of the same order of magnitude as the original cold-buzz values. As shown in figure 9, the amplitude of the attenuated cold-buzz pressure pulsations varied with the size of the disk (the smallest disk investigated resulted in the greatest attenuation). This phenomenon extended over a limited range of subcritical outlet-inlet area ratios.

High-speed shadowgraph pictures (fig. 10) were taken at approximately 2500 frames per second in order to study the shock-wave patterns at the diffuser inlet for the conditions corresponding to those of figure 8(b) for a disk size equal to 65 percent of the combustion-chamber area. Only one sequence of selected photographs (fig. 10(a)) is shown for the cold-buzz condition with the disk locked in position, because the only noticeable difference between the full-open and full-closed positions was the frequency of the pulsations. The shock patterns were otherwise similar. As indicated by the branch shocks in the photographs (fig. 10(a)), boundary-layer separation on the cone surface appeared to be associated with the cold-buzz condition, although its exact role (cause or effect) was not determined. A high order of mass flow spillage around the inlet was indicated by the main shock traveling upstream to the tip of the cone. Contrasted to this condition is the attenuated cold buzz, produced by the rotating disk tuned to a frequency of 104 cycles per second, and shown in a sequence of photographs (fig. 10(b)). The one obvious and significant change, effected by the rotating disk, was the large reduction in the shock travel ahead of the diffuser inlet, which would indicate a decrease in the rate of flow spillage from that of the original cold buzz (fig. 10(a)). 1400

SUMMARY OF RESULTS

An experimental investigation to determine the effect of pressure pulsations on supersonic diffuser performance was conducted in the NACA Lewis 20-inch supersonic tunnel on an 8-inch ram jet at a Mach number of 1.87. Experiments in which combustion roughness and controlled mechanical oscillations were studied resulted in the following observations:

1. Oscillations of the diffuser shock, generated by pressure pulsations from either the ram-jet combustion process or the rotating-disk oscillator, precluded the attainment of mean pressure recoveries that were equal to the optimum steady flow value. The annular regenerative burner, however, operated with such a low order of pressure pulsations that the resultant decrement in diffuser pressure recovery was quite small (approximately 1 percent of the optimum steady flow value).

2. Within the experimental accuracy, the optimum mean combustion-chamber static pressure occurred when the maximum instantaneous static pressure equaled the optimum steady-flow value.

3. In both the combustion and mechanical oscillation experiments, the decrement in optimum mean combustion-chamber static pressure was equal to one-half the total amplitude of the pressure pulsations.

4. The amplitude of cold-buzz pressure pulsations in a single-shock diffuser was markedly attenuated over a limited range of subcritical outlet-inlet area ratios by means of a properly tuned rotating disk located in the combustion chamber. With a disk size

equal to 30 percent of combustion-chamber area, the total amplitude of the pressure fluctuation was reduced by 92 percent and the ratio 1400 of the mean combustion-chamber static- to free-stream total pressure was increased by 7.4 percent when the rotating disk was tuned to a frequency of 106 cycles per second. The degree of cold-buzz attenuation varied inversely with the size of the disks investigated.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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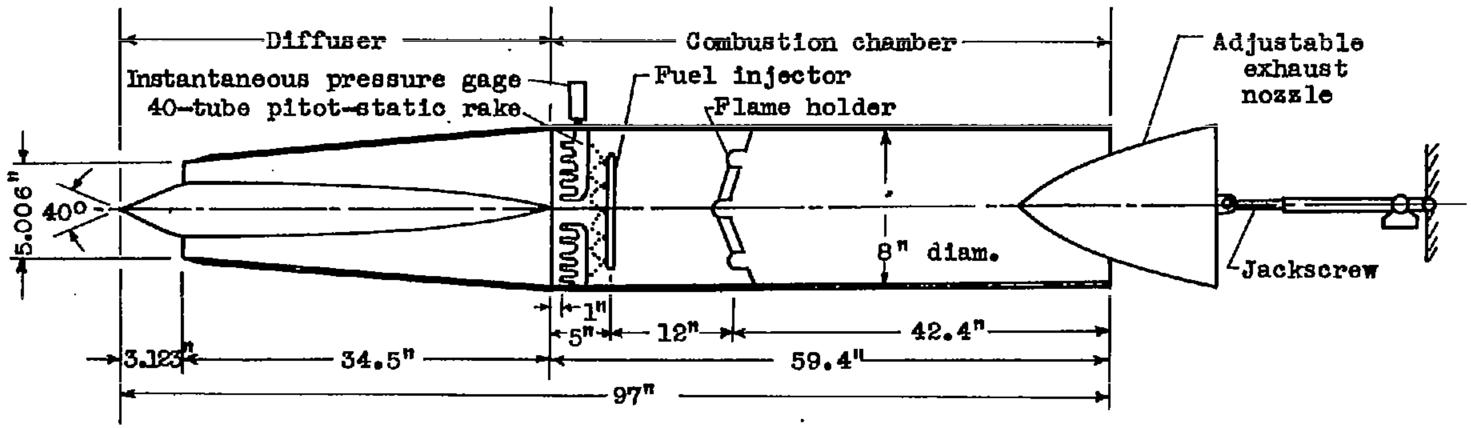
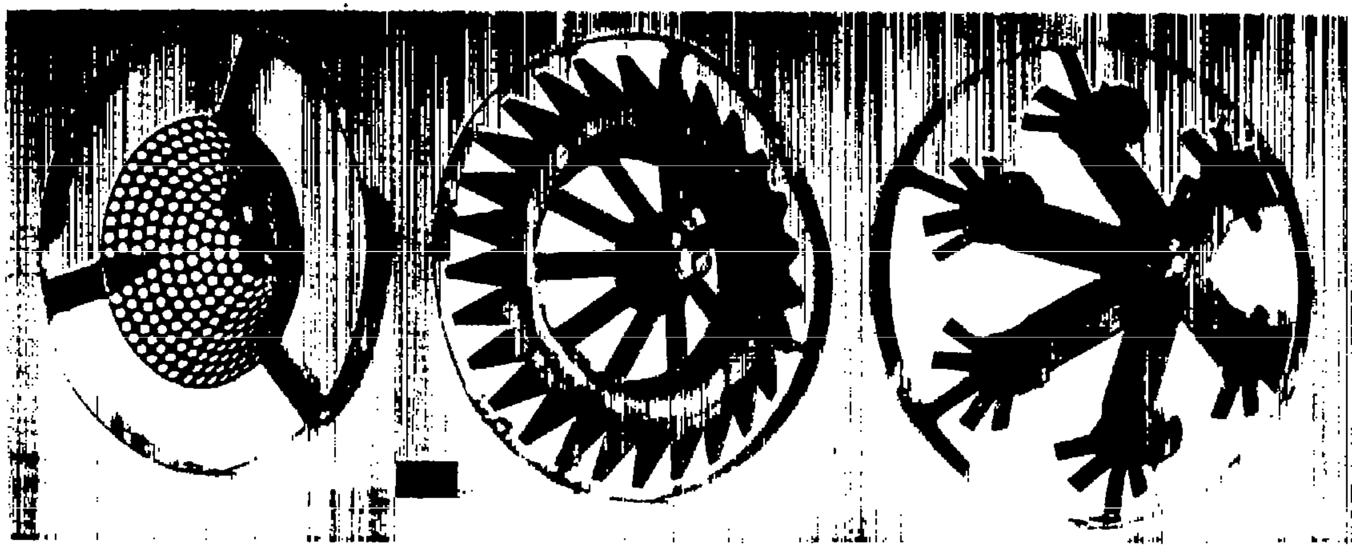
5. Dittrich, Ralph T.: Effects of Fuel-Nozzle Carbon Deposition on Combustion Efficiency of Single Tubular-Type, Reverse-Flow, Turbojet Combustor at Simulated Altitude Conditions. NACA TN 1618, 1948.



(a) Schematic diagram of 8-inch ram jet.



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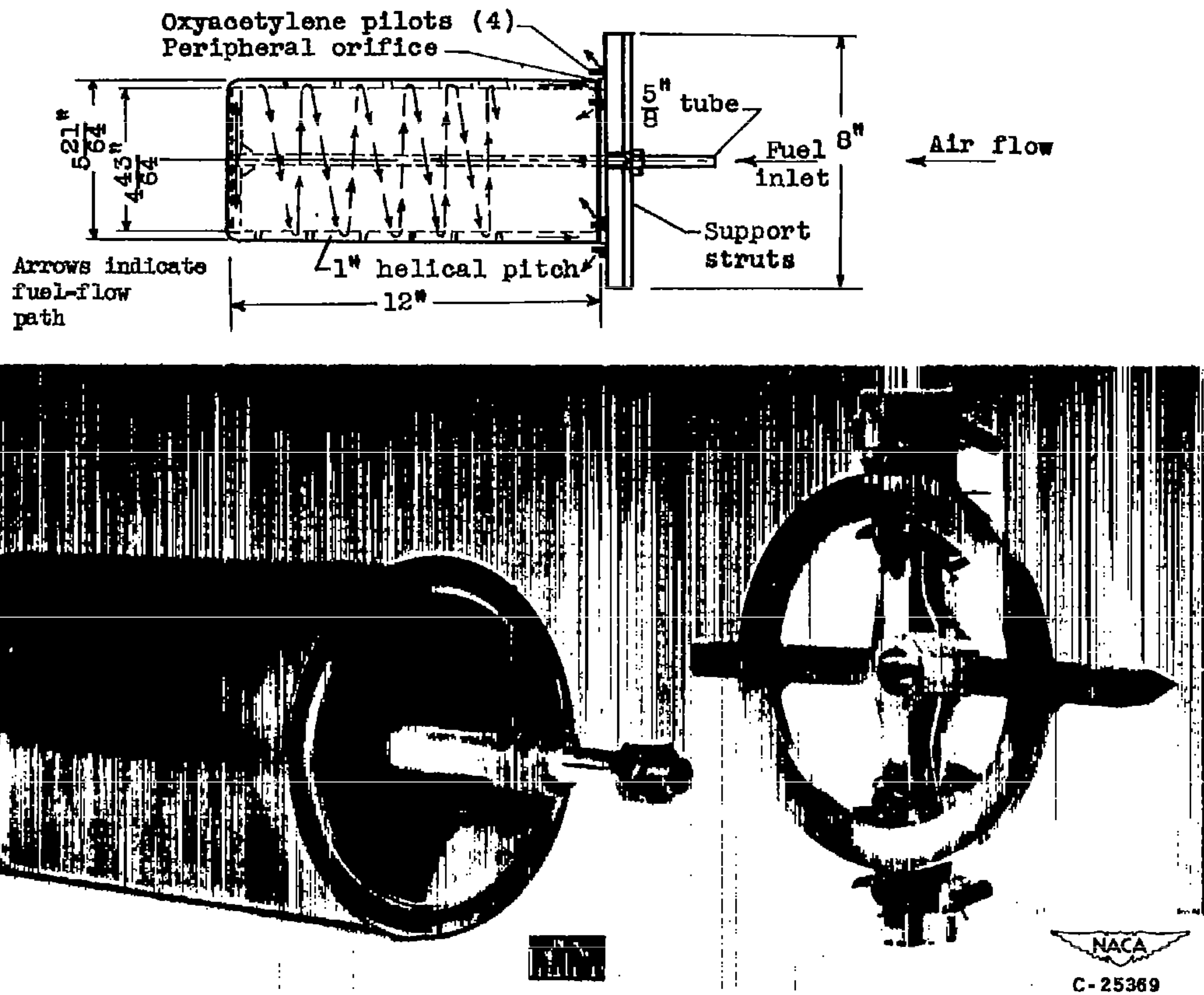
35-percent blockage 60-percent blockage 50-percent blockage

(b) Liquid fuel-injection burners (rear view).

Figure 1. - Experimental apparatus.



(c) Annular regenerative burner
Figure 1. - Continued. Experimental apparatus.

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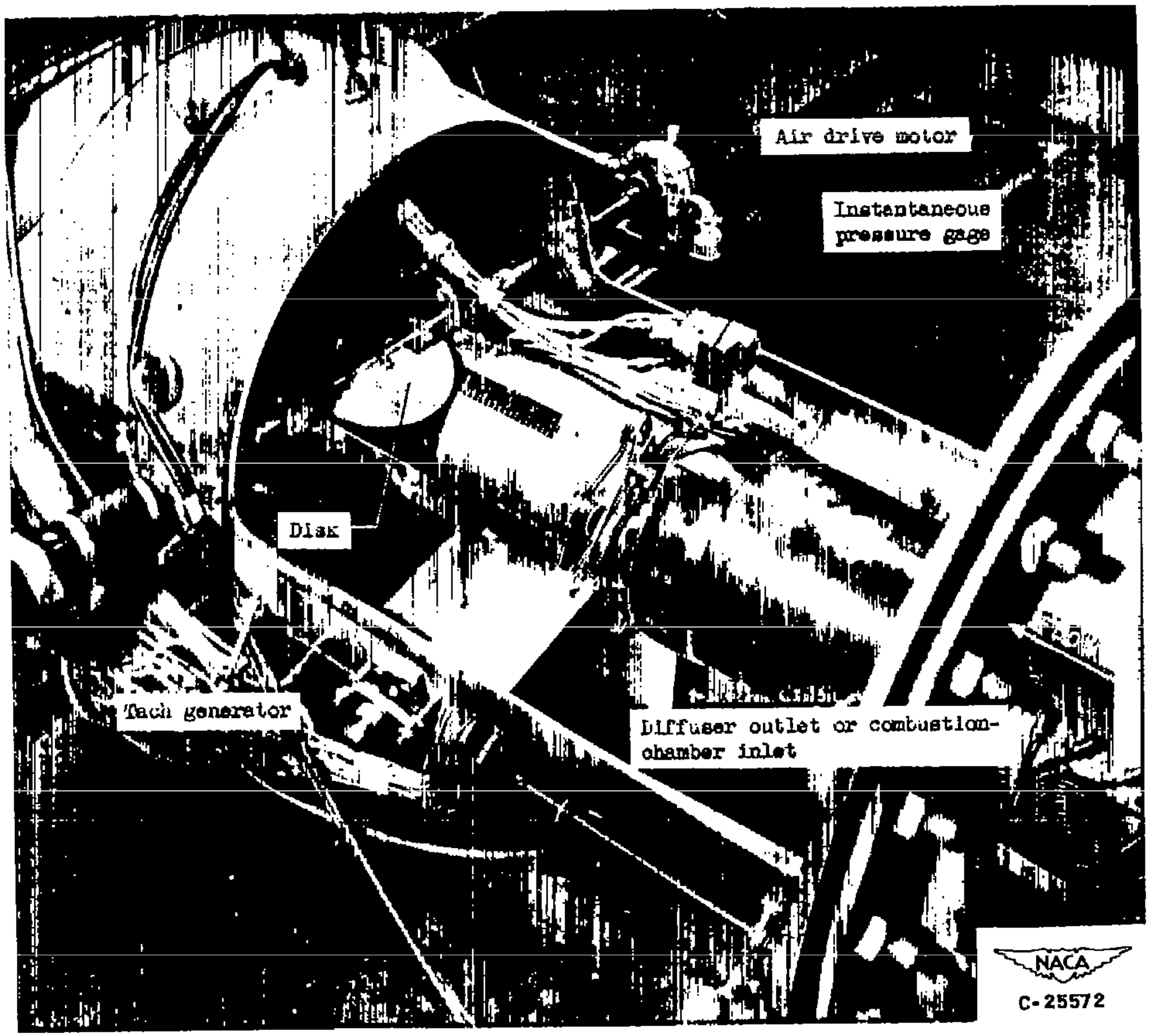

(d) Rotating-disk oscillator mounted in combustion chamber of 8-inch ram jet.

Figure 1. Concluded. Experimental apparatus.

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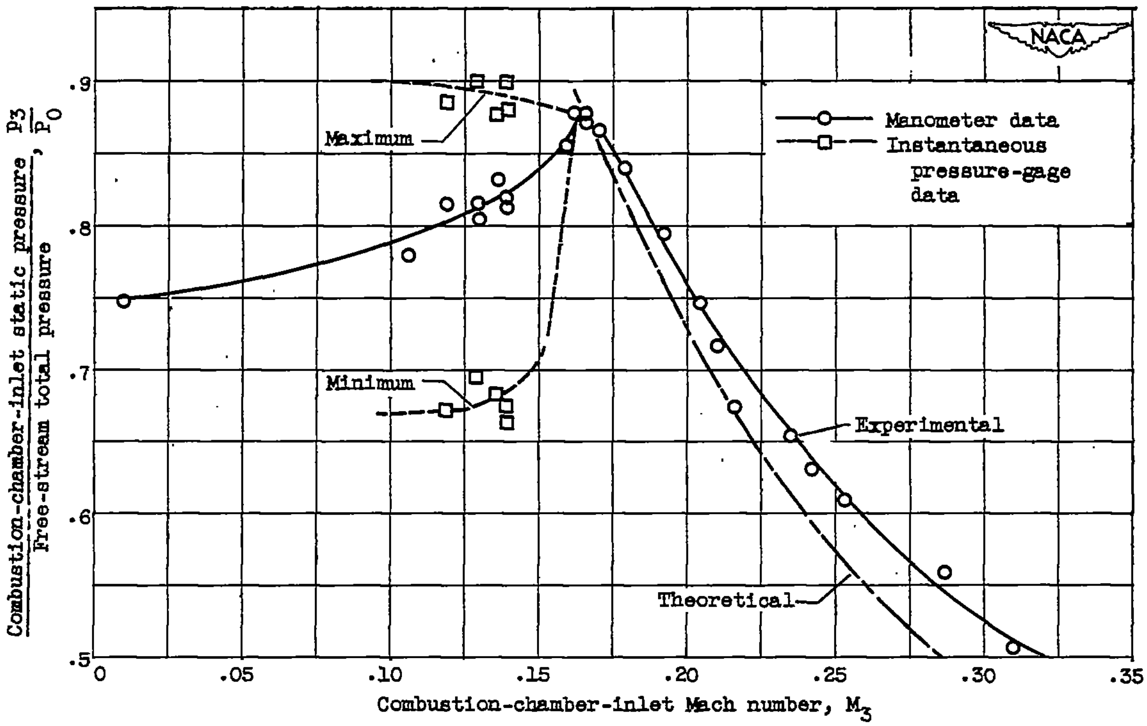

Figure 2. - Diffuser-performance curve obtained with steady-flow resistance and showing variation of combustion-chamber static pressures with combustion-chamber inlet Mach number.

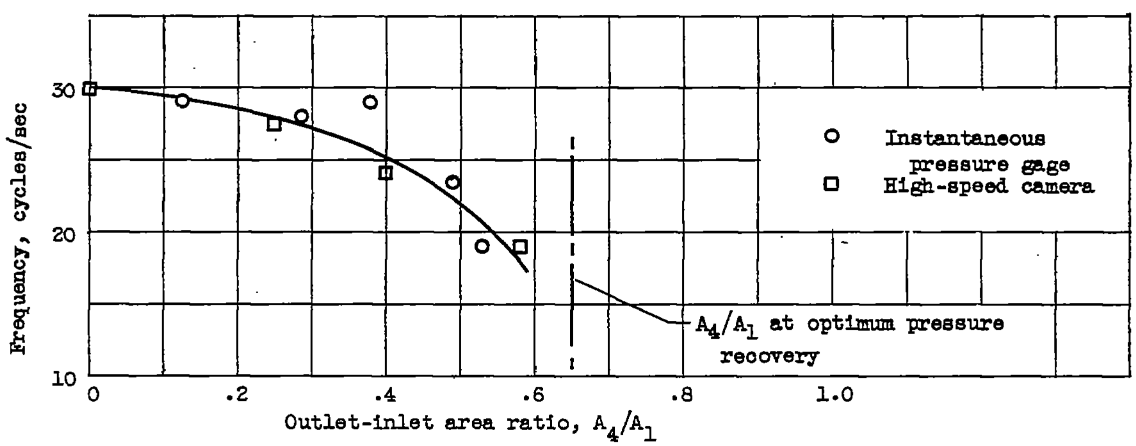

Figure 3. - Variation of cold-buzz frequency with outlet-inlet area ratio.

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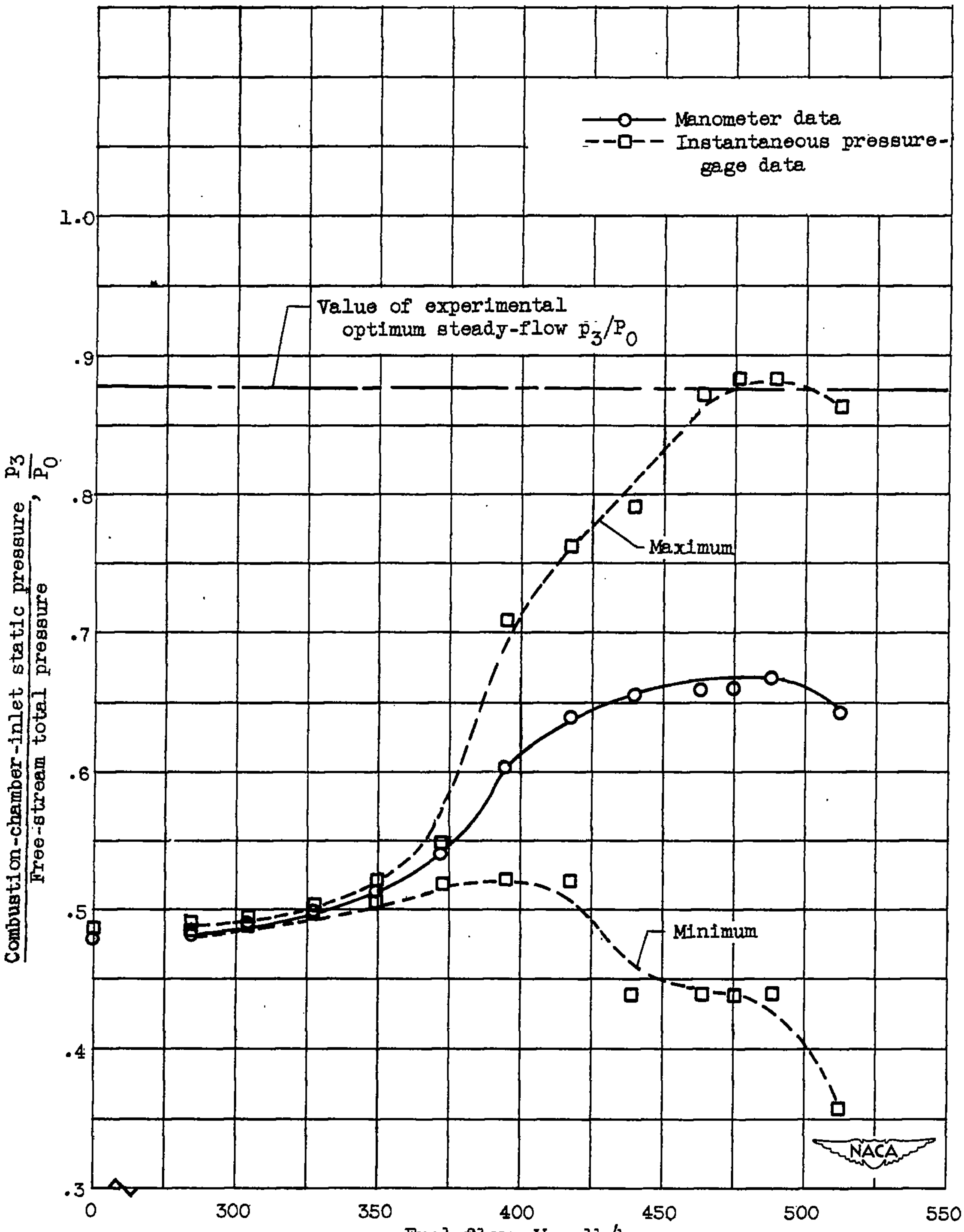

Figure 4. - Data from typical combustion experiment with liquid fuel-injection burners showing variation of combustion-chamber pressures with fuel flow. Constant outlet-inlet area ratio, 1.37; flame-holder blockage, 35 percent.

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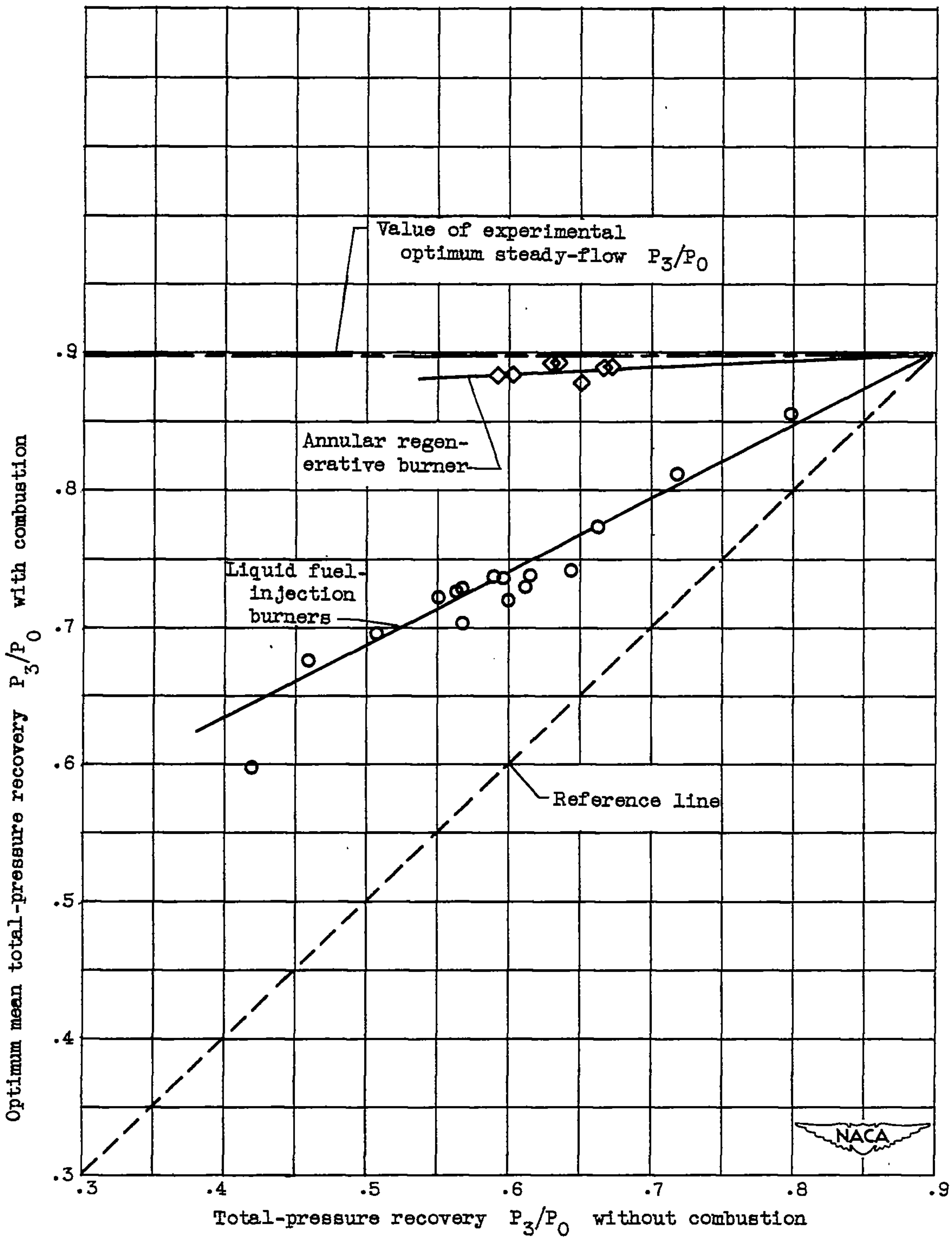
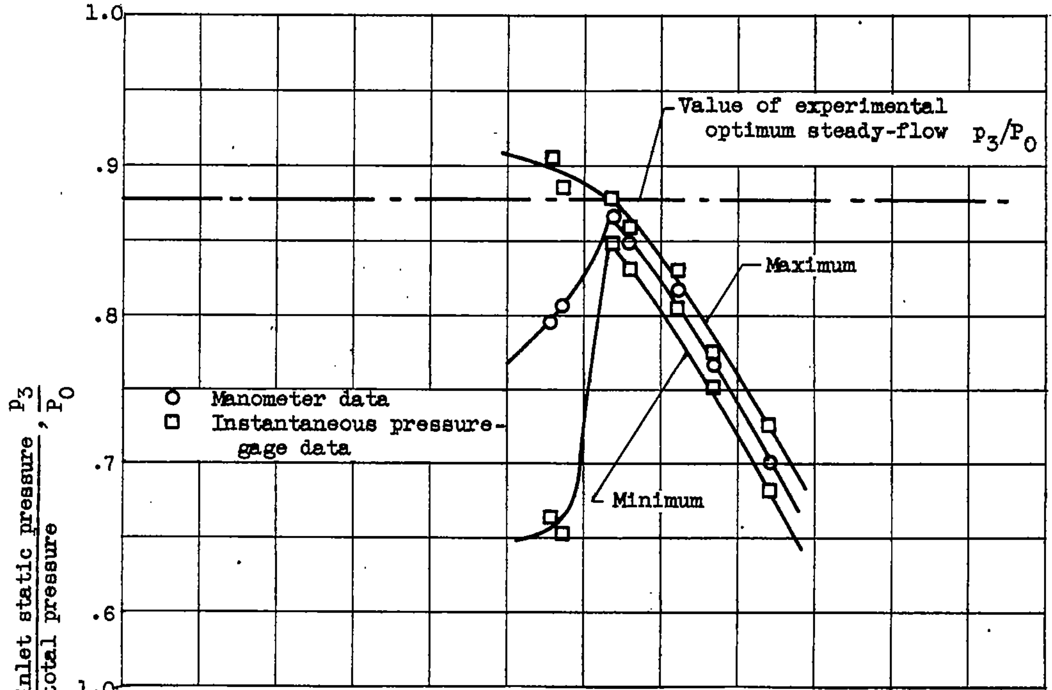
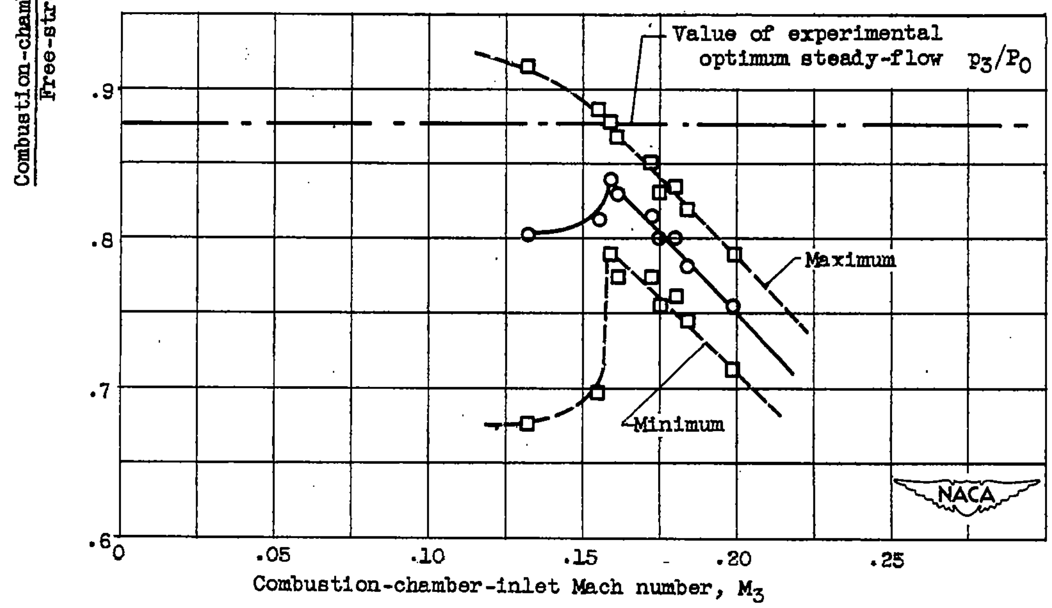


Figure 5. - Comparative optimum mean total-pressure recoveries obtained with combustion in 8-inch ram jet using liquid fuel-injection burners and annular regenerative burner.



(a) Disk size, 55 percent of combustion-chamber area; frequency, 60 cycles per second.



(b) Disk size, 70 percent of combustion-chamber area; frequency, 60 cycles per second.

Figure 6. - Data from typical rotating-disk oscillator experiments showing variation of combustion-chamber pressures with combustion-chamber-inlet Mach number.

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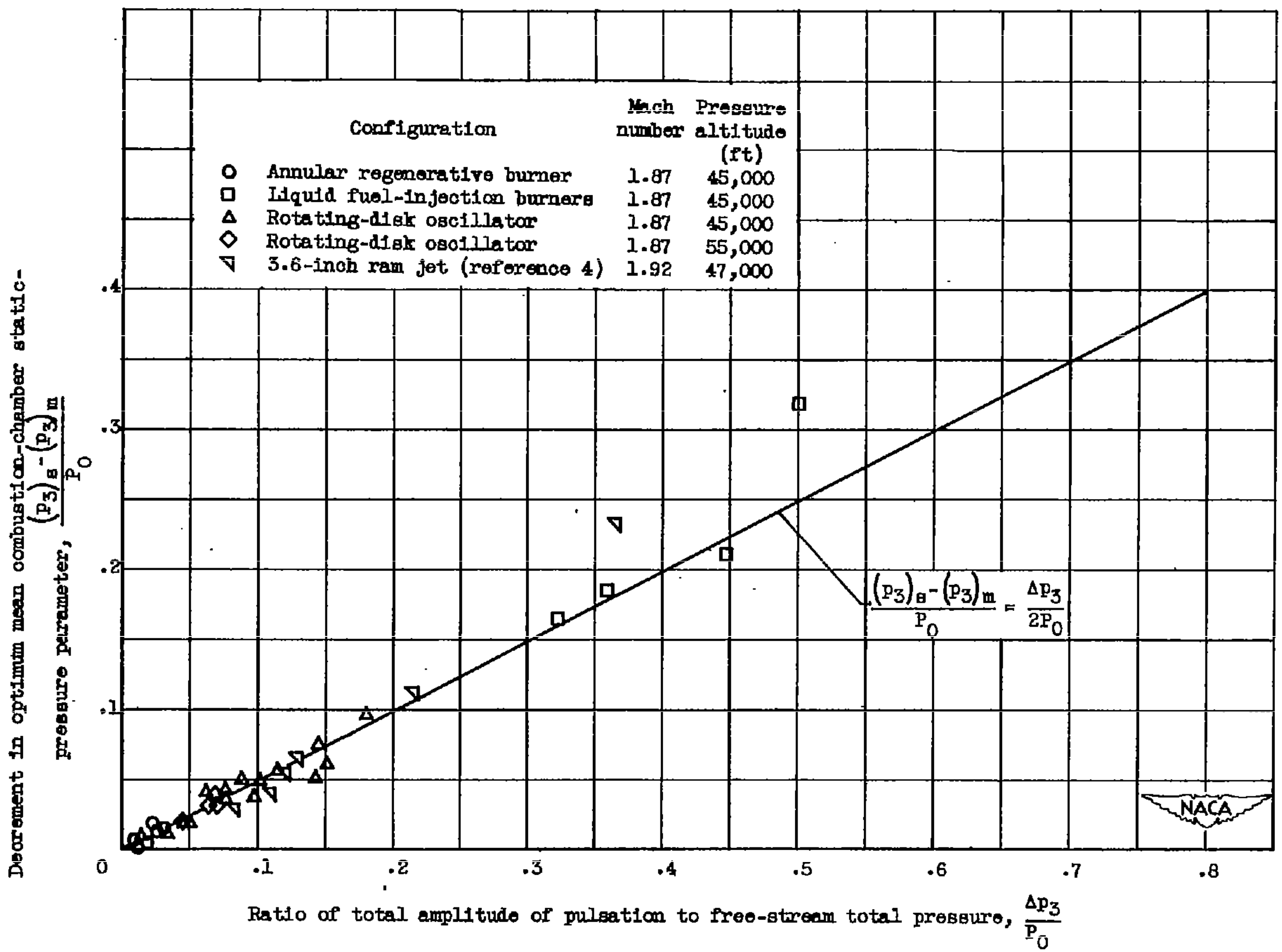
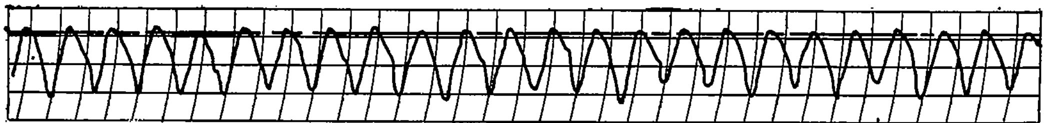
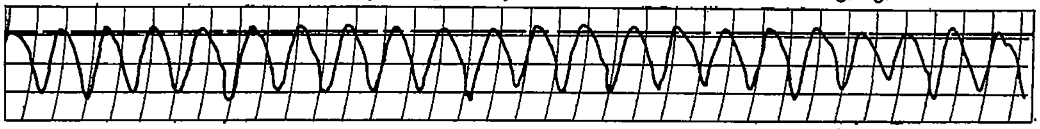


Figure 7. - Correlation of hot and cold data showing decrement in optimum mean combustion-chamber static pressure as function of pulsation amplitude.



Disk locked (full closed); frequency, 16.5 cycles per second; p_3/P_0, 0.811.



Disk locked (full open); frequency, 15.5 cycles per second; p_3/P_0, 0.813.

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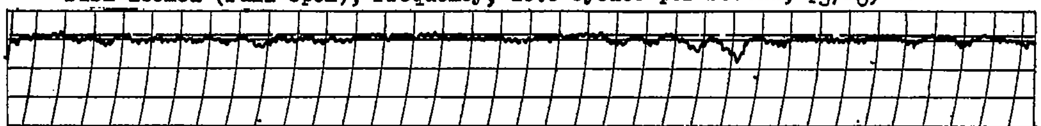
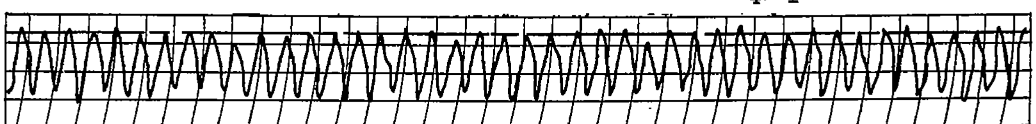
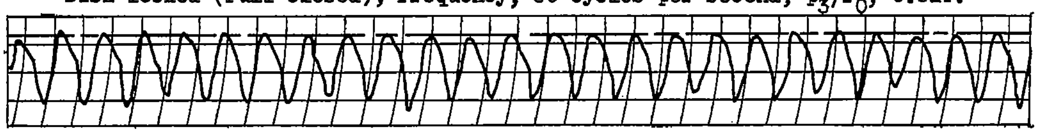


Oscillator frequency, 106 cycles per second; p_3/P_0, 0.871.

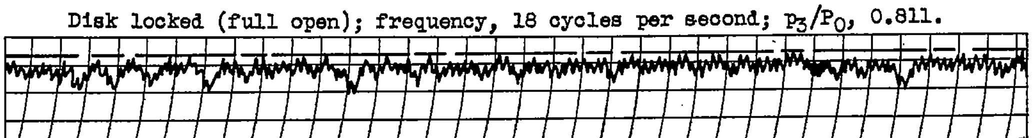
(a) Disk size, 30 percent of combustion-chamber area; A_4/A_1, 0.57.



Disk locked (full closed); frequency, 30 cycles per second; p_3/P_0, 0.814.

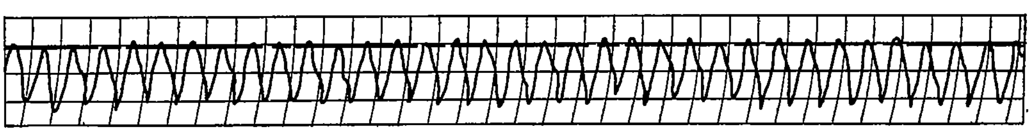


Disk locked (full open); frequency, 18 cycles per second; p_3/P_0, 0.811.

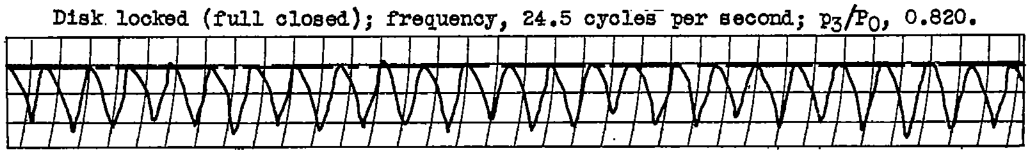


Oscillator frequency, 104 cycles per second; p_3/P_0, 0.835.

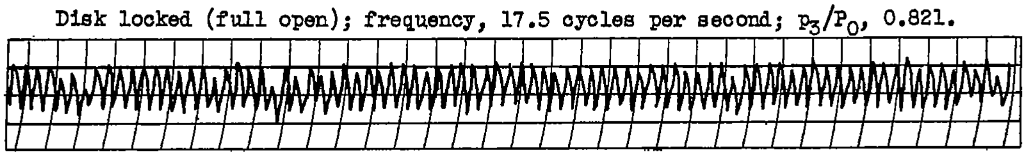
(b) Disk size, 65 percent of combustion-chamber area; A_4/A_1, 0.56.



Disk locked (full closed); frequency, 24.5 cycles per second; p_3/P_0, 0.820.



Disk locked (full open); frequency, 17.5 cycles per second; p_3/P_0, 0.821.



Oscillator frequency, 62 cycles per second; p_3/P_0, 0.831.

(c) Disk size, 75 percent of combustion-chamber area; A_4/A_1, 0.50

Figure 8. - Attenuation of cold-buzz pressure fluctuations by means of rotating-disk oscillator mounted in combustion-chamber of 8-inch ram jet.

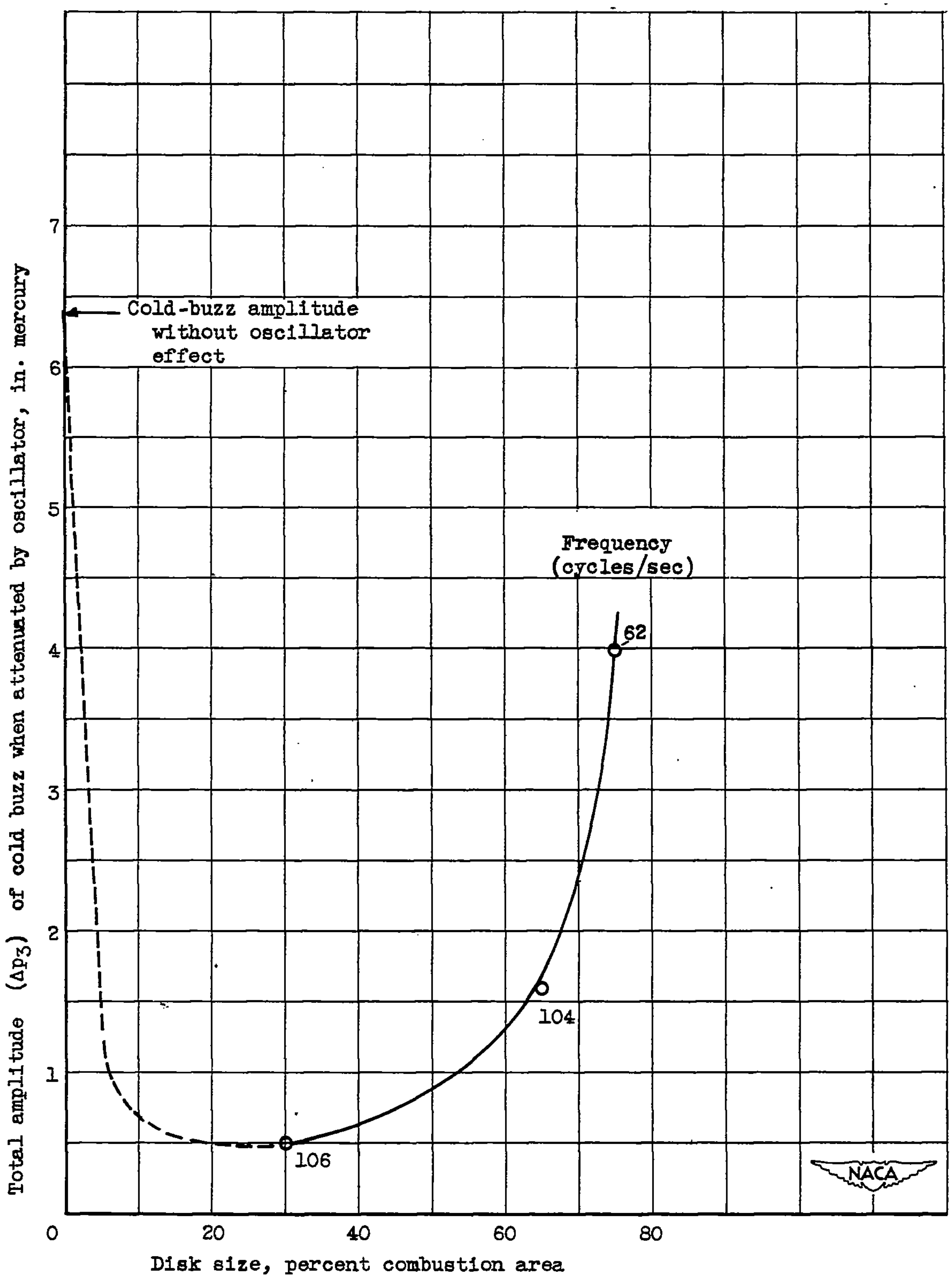
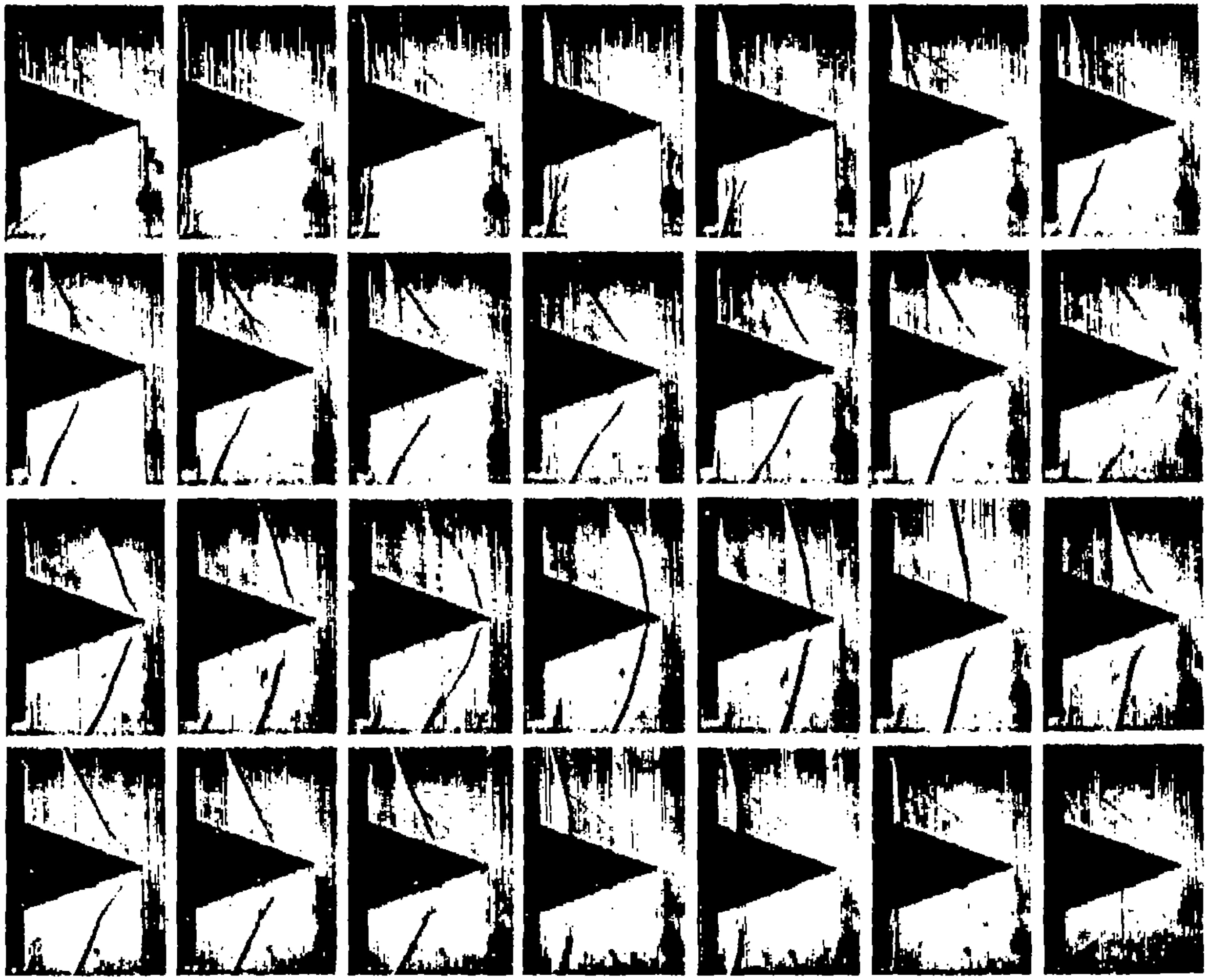


Figure 9. - Variation in amplitude of attenuated cold-buzz-pulsations with three disk sizes investigated.



(a) Cold buzz with oscillator disk locked in position. Frequency, 20 cycles per second; p_3/P_0, 0.81; A_4/A_1, 0.56.

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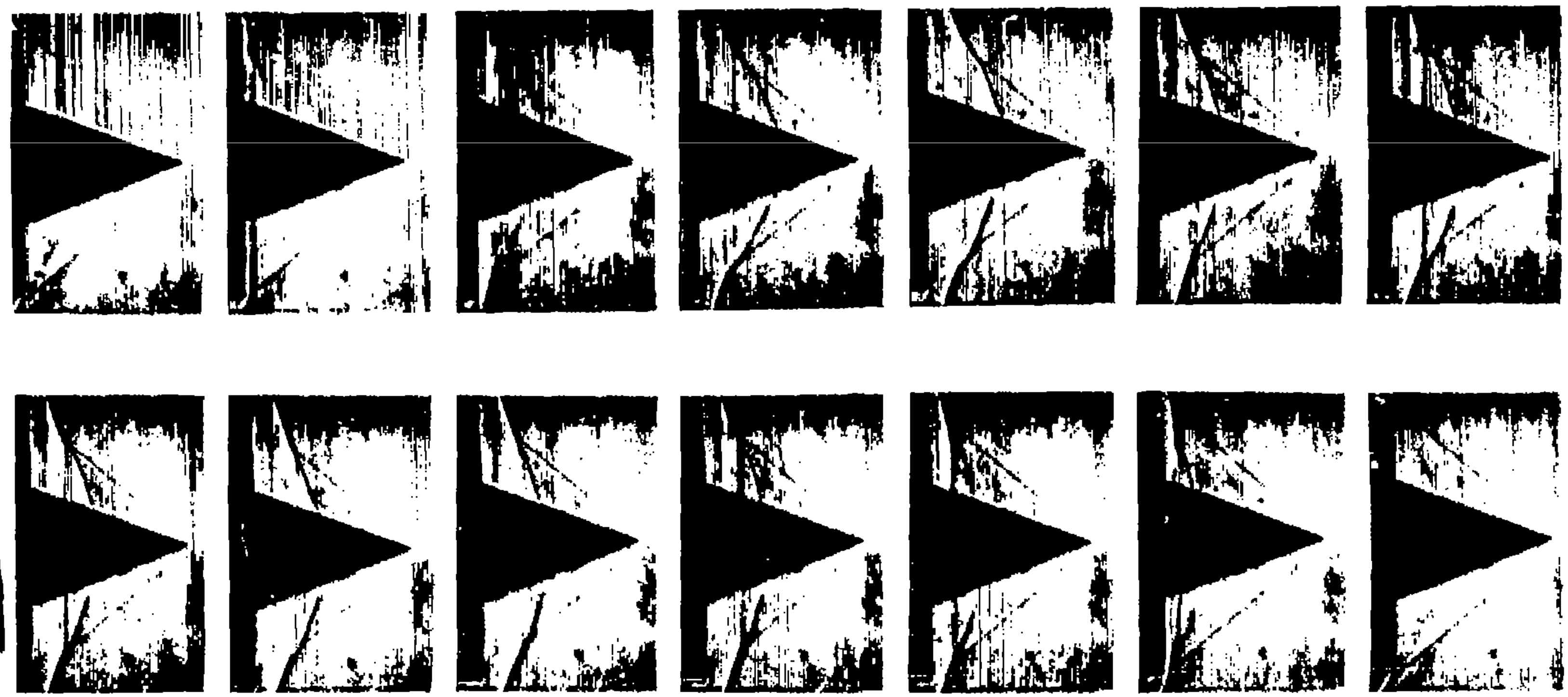
Figure 10. - High-speed shadowgraph pictures of shock pattern at diffuser inlet.



(b) Attenuated cold buzz, disk size = 65 percent of combustion-chamber area. Frequency, 104 cycles per second; p_3/P_0, 0.835; A_4/A_1, 0.56.

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Figure 10. - Concluded. High-speed shadowgraph pictures of shock pattern at diffuser inlet.